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Final Report*

Climatic Effect of Impact-Induced Stratospheric Hazes in Jupiter

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The impact of each fragment of comet Shoemaker-Levy/9 into Jupiter resulted in a high altitude, dark haze in the upper troposphere and stratosphere of the planet. To study the perturbation induced by these hazes on the equilibrium temperature structure of Jupiter's atmosphere, I proposed to modify an existing atmospheric radiative-convective equilibrium code. I originally developed this code in collaboration with NASA/Ames collaborator Chris McKay to study the atmospheres of Uranus and Neptune (Marley et al. 1996a). The goal of the originally-proposed consortium agreement was to determine the extent to which absorption of solar radiation by the hazes heated the atmosphere after the impacts.

While the code was under development, it became apparent that a more interesting application of the radiative-convective model would be the atmosphere of the newly discovered brown dwarf Gliese 229B (Nakajima et al. 1995; Oppenheimer et al. 1995). Brown dwarfs are objects more massive than planets, but less massive than the smallest stars. They had long been known only as theoretical constructs. As the first unimpeachable brown dwarf Gliese 229B provided the opportunity to apply the theoretical model developed for the jovian planets of our solar system to an entirely new object. Thus, in concurrence with Ames collaborator McKay, the consortium research effort was redirected to the study of the atmosphere of Gl229B.

Observations of the brown dwarf provided a near-infrared spectrum from 1.0 to 2.5 μm and broad-band fluxes from 3.5 to 14 μm (Matthews et al. 1996; Kulkarni et al. 1996; Figure 1). From the observed bolometric flux, it was clear that the object was a brown dwarf. No stars have luminosities less than 5×10^{-5} times that of the sun, yet Gl229B had a luminosity of only 6×10^{-6} that of the sun. However the effective temperature, T_{eff}, and mass of the object was not well constrained. Only by comparing atmosphere models to the observed spectrum could these characteristics of the brown dwarf be inferred.

To compute the atmospheric temperature profile for brown dwarfs in the relevant temperature range (600 to 1200 K), I adapted the radiative-convective model to brown dwarf conditions. This entailed extending the modeled spectral range in the thermal infrared to 0.5 μm and enlarging the temperature range over which the various opacities were computed. Several new opacity sources also were incorporated into the model, as detailed below. I assumed a standard solar composition for the bulk of the atmosphere. Refractory elements (for example, Fe, Ti, and silicates) condense deep in the atmosphere for effective temperatures $T_{eff} \sim 1000$K and thus have

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negligible gas-phase abundances near the visible atmosphere, as is also true in the atmosphere of Jupiter (T_{eff} = 124K). For an atmosphere similar to that of Gl 229B, chemical equilibrium calculations revealed that C, N, O, S, and P will be found mainly in the form of CH_4, NH_3, H_2O, H_2S, and PH_3, respectively. However, deep in the atmosphere, chemical equilibrium favors CO over CH_4 and N_2 over NH_3. The model atmosphere incorporates opacities of these molecules, molecular hydrogen, and He in their respective solar abundances and includes no other elements.

The opacity calculations included collision-induced absorption by H_2-H_2 and H_2-He, free-free absorption by H_2^-, bound-free absorption by H^-, and Rayleigh scattering. The absorptions of NH_3, CH_4, and PH_3 were calculated using the HITRAN data base with corrections and extensions. Additional tabulations were used where necessary for CH_4, especially shortwards of 1.6μm. Data for H_2O and H_2S were computed from a direct numerical diagonalization by R.B. Wattson (personal communication). Absorption by CO and PH_3 was included in the spectral models, but not in the temperature profile computation. The baseline models assume the atmosphere to be free of clouds. Richard Freedman, also of Ames, collaborated in the handling of and computation of the opacities. Once a temperature profile was calculated, it was used by project collaborators Didier Saumon and Tristan Guillot at the University of Arizona to compute a high resolution spectral model of the brown dwarf.

The computed spectra (Fig. 1) are a good match with the data in the 1.2 to 1.8 μm window, but they deviate at 1 μm, in the window centered on 2.1 μm, and in regions of low flux. The best fitting models reproduce the observed broadband fluxes reasonably well. Although many individual spectral features of CH_4 and H_2O are reproduced, particularly near 1.7 and 2.0 μm, the overall band shapes are not well accounted for in the region from 1 to 2.5 μm. I attribute these discrepancies to a poor knowledge of the CH_4 opacity and, to a lesser extent, of the H_2O opacity. Given these uncertainties, the best fits for the bolometric luminosity, the observed spectrum, and the photometry give combinations of T_{eff} and g lying in the range 850 K < T_{eff} < 1100 K and g < 3000 m sec^{-2}. Lower Teff values are allowed for g< 300 m sec^{-2}, but the shapes of the J and H bands increasingly deviate from the observations. The high-T_{eff} limit arises from the inability to simultaneously fit the bolometric luminosity and the 10-μm flux.

This adaptation of a radiative-convective atmosphere model originally developed to study the atmospheres of the jovian planets to the brown dwarf Gliese 229B permitted new constraints to be placed on the properties of the brown dwarf. I found that the effective temperature is near 960K and the mass lies in the range 30 to 55 times Jupiter's mass. These same models were also used as boundary conditions to compute the thermal evolution of the brown dwarf through time. Results of that research are reported in Marley et al. (1996b).

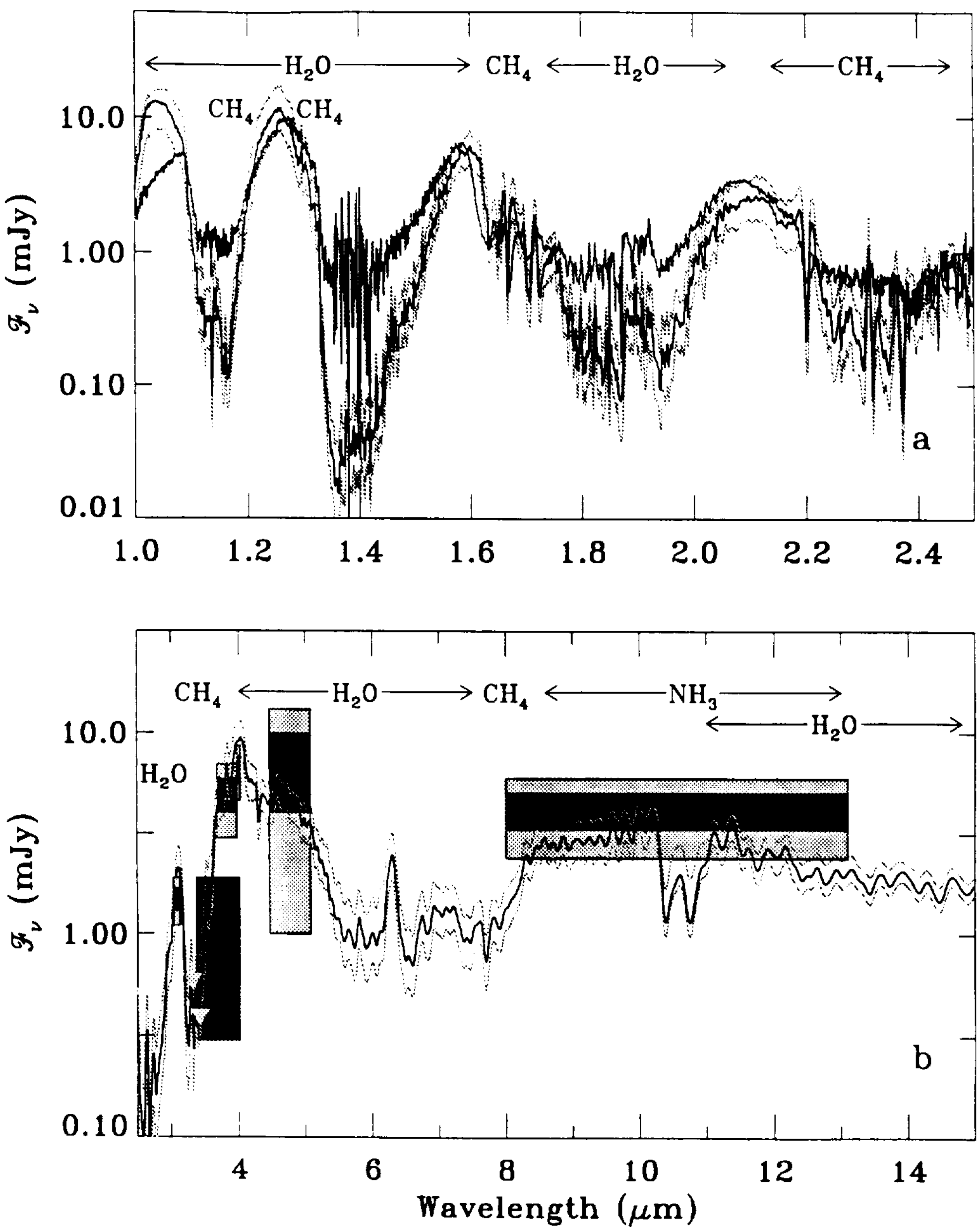

Fig 1. **(A)** Synthetic spectra (thick lines) for (bottom to top) T_{eff} = 890K, 960K, 1030 K, and g = 1000 m sec^{-2}, together with data (thin line). The three curves in **(B)** are calculated for the same values of T_{eff} and g; boxes show the photometric measurements with bandpasses indicated by their width. Dark boxes show the 1-sigma error on the measurements and the lighter boxes show the 2-sigma error. Triangles show upper limits to narrow-band fluxes. In both (A) and (B), spectral intervals are labeled with the molecules primarily responsible for the opacity in that interval.

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